Water Ecology and Food Security Analysis of Spring Maize Single Cropping as an Alternative to Wheat-Maize Double Cropping in the Hebei Low Plain: Postprint

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Abstract

A field experiment was conducted from 2011 to 2014 in Wuqiao County, Hebei Province to address the increasingly severe water shortage in the Hebei low plain area. Using the wheat-maize double cropping system (WS) as a control, two spring maize monoculture planting patterns were established: zero-irrigation spring maize monoculture (SMRF) and suitable-water spring maize monoculture (SMSW), making a total of three treatments, to investigate the feasibility of replacing the traditional high water-consuming wheat-maize double cropping system with spring maize monoculture in this region. The results showed that: compared with WS, the annual water consumption of SMSW and SMRF decreased by 48.4% and 54.2%, respectively; winter wheat water consumption mainly came from irrigation water and soil water storage, with rainfall during the experimental years only meeting 32.9% of the total winter wheat water consumption; water consumption during the spring maize growth period mainly came from rainfall, with the total effective rainfall during the growth period in the experimental years meeting 91.9% and 94.9% of the total spring maize water consumption for SMSW and SMRF, respectively. The annual yields of SMSW and SMRF decreased by an average of 24.4% and 45.8% compared with WS, respectively. The water use efficiency of SMSW and SMRF was 24.8% and 0.3% higher than that of WS, respectively. The economic benefits of SMSW and SMRF decreased by an average of 5.2% and 36.8% compared with WS, respectively. The economic water use efficiency of SMSW and SMRF was 56.7% and 17.5% higher than that of WS, respectively. Currently, WS still maintains certain advantages in yield and benefit over SMSW, but WS relies heavily on groundwater irrigation; whereas SMSW exhibits significantly higher water use efficiency and economic water use efficiency than WS. With the maturation of

high-yield spring maize technology systems and further improvement of spring maize yields, and under the "new normal" of simultaneous increases in total grain production, grain stocks, and grain imports in China, switching from wheat-maize double cropping to spring maize monoculture in this region offers feasibility for balancing water ecology and food security.

Full Text

Security of Water-Ecology and Food Under Replacement of Winter Wheat-Summer Maize Rotation with Spring Maize Mono-Cropping in Hebei Lowland Plains

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Abstract

Hebei Lowland Plains, one of China' s main grain-producing regions, faces acute water shortages that threaten sustainable agricultural development. To address this challenge, field experiments were conducted at the Wuqiao Experiment Station in Hebei Province from 2011-2014 to evaluate the feasibility of replacing the traditional high water-consuming winter wheat-summer maize double-cropping system (WS) with spring maize mono-cropping systems. Three treatments were implemented: WS as the control, a rain-fed spring maize mono-cropping system (SMRF), and a fully-irrigated spring maize mono-cropping system (SMSW). Four key performance indicators were evaluated: actual annual evapotranspiration (ETa), productivity, water use efficiency (WUE), and economic water use efficiency (EWUE).

Results demonstrated that SMSW and SMRF reduced average annual ETa by 48.4% and 54.2%, respectively, compared to WS. Under the WS system, precipitation accounted for only 32.9% of winter wheat' s total water consumption, with irrigation and soil water storage comprising the remainder. In contrast, precipitation supplied 91.9% and 94.9% of water needs for SMSW and SMRF, respectively. Average annual productivity decreased by 24.4% under SMSW and 45.8% under SMRF relative to WS. However, WUE increased by 24.8% for SMSW and 0.3% for SMRF compared to WS. Economic benefits under SMSW were only 5.2% lower than WS, while SMRF showed a 36.8% reduction. Notably, EWUE was substantially higher for SMSW and SMRF, increasing by 56.7% and 17.5%, respectively, over WS.

While WS currently maintains yield and economic advantages, its heavy reliance on groundwater irrigation is unsustainable. SMSW exhibits significantly higher

WUE and EWUE, and with advancing spring maize production technologies and China' s "new normal" of simultaneous increases in grain production, storage, and imports, transitioning from wheat-maize double-cropping to spring maize mono-cropping offers a viable strategy that balances water ecological security with food security in the region.

Keywords: Hebei Lowland Plains; Wheat-maize double-cropping system; Spring maize mono-cropping system; Evapotranspiration; Productivity; Water use efficiency; Economic benefits

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1.1 Study Site Overview

Field experiments were conducted from October 2011 to October 2014 at the Wuqiao Experiment Station of China Agricultural University in Wuqiao County, Hebei Province (37°41 N, 116°37 E). Located in the central Heilonggang River basin of the Haihe Lowland Plains, the region features a warm temperate monsoon climate. The average annual precipitation from 1990–2014 was 568 mm, with 50-80% of rainfall concentrated in June–August. The wheat season received approximately 120 mm of precipitation, while annual evaporation reached 1,700 mm. The region enjoys 2,340 sunshine hours annually and accumulated temperature above 10°C of 4,665°C.

Monthly cumulative precipitation during the experimental period (October 2011–October 2014) is shown in [Figure 1: see original paper]. Total annual rainfall was 698 mm in 2012, 611 mm in 2013, and 422 mm in 2014. Using the domestic classification standard for rainfall years [18], the experimental years were categorized into three types based on annual precipitation relative to the 1990–2014 mean (P = 568 mm) and standard deviation ( ). Wet years were defined as Pi > P + 0.33 , dry years as Pi < P - 0.33 , and normal years as intermediate. This classification identified 2012 as a wet year (>618 mm), 2013 as a normal year (518-618 mm), and 2014 as a dry year (<518 mm), with 2014 receiving 146 mm less than the long-term average.

The experimental soil profile consisted of loam in the 0–80 cm layer, a clay pan at 80–160 cm, and sandy soil below 160 cm. The 0–40 cm layer had an average bulk density of 1.6 g·cm ^{3}, field capacity of 20.6%, and permanent wilting coefficient of 6.9%.

1.2 Experimental Design and Methods

The experiment comprised three treatments: winter wheat-summer maize double-cropping (WS), rain-fed spring maize mono-cropping (SMRF), and fully-irrigated spring maize mono-cropping (SMSW). Each treatment had three replicates in plots measuring 5 m × 16 m (80 m^2). Winter wheat (WW) cultivar ‘Jimai 22’ , summer maize (SM) cultivar ‘Zhengdan 958’ , and spring maize cultivar ‘Jinhai 5’ were used.

The WS treatment followed local conventional practice with fixed irrigation of 300 mm per annual cycle, applied four times: 75 mm before wheat sowing, at wheat regreening, at wheat flowering, and before maize sowing. For SMSW, soil moisture thresholds were set at 65% of field capacity (0–40 cm) during the seedling stage, and 70% during jointing, large trumpet, and heading stages [19]. Soil moisture was measured every 7-10 days, and irrigation was applied to restore moisture to field capacity when thresholds were breached. Total irrigation was recorded cumulatively. All plots used flood irrigation with individual water meters. Other management practices are detailed in .

1.2.1 Data Collection

Meteorological data: Precipitation data were obtained from the Wuqiao County Meteorological Bureau, located approximately 800 m from the experimental site.

Irrigation amount: WS followed the predetermined schedule. For SMSW, soil volumetric water content (0–40 cm) was measured using a German TRIME-PICO portable soil moisture meter at 7-10 day intervals. Single irrigation quota and seasonal irrigation amount were calculated using:

$$\text{Irrigation quota (mm)} = H \times (\theta_f - \theta_c) \quad (1)$$

where H is soil layer depth (mm), f is field capacity (volumetric water content) of 0–40 cm, and c is pre-irrigation volumetric water content of 0–40 cm. Seasonal irrigation was the sum of all individual applications.

Soil gravimetric water content: Determined by oven-drying method at 20 cm intervals to 200 cm depth at one representative point per plot, measured before sowing and after harvest.

Soil bulk density: Measured by core method at 20 cm intervals to 200 cm depth at one representative point per plot, before sowing and after harvest.

Inputs and outputs: All agricultural inputs (seed, pesticide, fertilizer, water, electricity) and labor/machinery costs were recorded. Labor costs were calculated at local wage rates: 35 yuan · person ^{1} · day ^{1} (8 h) for female workers and 40 yuan · person ^{1} · day ^{1} (8 h) for male workers. Grain prices from 2012–2014 were obtained from the *China Agricultural Product Price Survey Yearbook* to calculate economic outputs.

Yield: At maturity, three uniform 5 m^2 sampling areas per plot were harvested, threshed, and dried to calculate yield (grain moisture content 13.5%).

Annual yield: The sum of economic grain yields per unit land area over the entire year (grain moisture content 13.5%).

1.2.2 Soil Moisture Content and Economic Benefit Calculations

0-200 cm soil volumetric water content:

Crop water consumption (ETa) was calculated using the field water balance equation:

$$ETa = R + I - \Delta W$$

where ETa is evapotranspiration (mm), R is rainfall (mm), I is irrigation (mm), and ΔW is the change in soil water storage between sowing and harvest. Surface runoff was negligible due to deep groundwater (9 m) and flat terrain, and was omitted from calculations.

Infiltration was calculated using the recharge coefficient method from Sun et al. [20]:

$$Q = \alpha \times (R + I)$$

where is the leakage recharge coefficient: = 0.1 when 5-day cumulative rainfall 90 mm, = 0.15 when between 90-250 mm, and = 0.2 when 250 mm.

Water use efficiency (WUE):

Soil water storage:

Economic water use efficiency (EWUE):

where Y is crop yield and E is output value.

1.3 Statistical Analysis

Data were organized and graphed using Microsoft Excel 2010. Statistical analyses were performed using SPSS 18.0.

2.1 Water Consumption Characteristics of Different Cropping Patterns

From 2012-2014, winter wheat season rainfall ranged 118.5-133.8 mm, while summer maize season rainfall ranged 288.5-564.5 mm. Regardless of rainfall year type, winter wheat rainfall was insufficient to meet crop demand, with irrigation (225 mm) comprising the main water source. In contrast, rainfall was the primary water source for summer maize, supplying 85.4% of water needs in the wet year (2012) and 74.9% in the dry year (2014), even with 75 mm irrigation.

For spring maize systems, 2012-2014 seasonal rainfall ranged 314.6-514.9 mm, serving as the main water source. In SMSW, irrigation accounted for 22.5% and 13.7% of total water consumption in wet and normal years, respectively, but increased to 32.5% in the dry year.

Soil water storage (0-200 cm) decreased during winter wheat seasons by 48.6-100.4 mm, while increasing during summer maize seasons by 31.5-96.5 mm. SMRF spring maize also depleted soil water by 9.6-95.4 mm, with minimal depletion in wet years and maximum depletion in dry years. SMSW increased soil water storage by 8.4-26.5 mm in wet and normal years, but showed depletion in the dry year.

Annual water consumption followed the pattern WS > SMSW > SMRF. WS ranged 672.9-905.1 mm, SMSW 431.4-511.8 mm, and SMRF 371.6-482.7 mm (). In the wet year 2012, SMSW and SMRF reduced consumption by 48.4% and 54.2% compared to WS. In the normal year 2013, reductions were 34.5% and 38.7%, respectively. All systems showed reduced consumption in the dry year 2014, with SMSW and SMRF achieving 35.9% and 44.8% reductions versus WS.

2.2 Grain Yield Comparison of Different Cropping Patterns

Yield trends were consistent across single-season and annual yields from 2012-2014 ([Figure 2: see original paper]). Annual yields were significantly higher for WS (12,637.7-15,864.8 kg · hm ^{2}) than SMSW (9,007.8-12,485.4 kg · hm ^{2}) and SMRF (7,140.3-8,435.1 kg · hm ^{2}) ($P < 0.05$). Compared to WS, SMRF and SMSW reduced average annual yields by 24.3% (3,454.0 kg · hm ^{2}) and 45.7% (6,500.5 kg · hm ^{2}), respectively.

Single-season yields ranked SMSW > SMRF > SM (summer maize) > WW (winter wheat). SMSW exceeded WW and SM by 60.1% (4,036.9 kg · hm ^{2}) and 43.6% (3,265.8 kg · hm ^{2}), respectively, while SMRF exceeded WW and SM by 14.7% (990.4 kg · hm ^{2}) and 2.9% (219.3 kg · hm ^{2}), respectively.

2.3.1 Water Use Efficiency

Significant differences in WUE were observed among cropping patterns from 2012-2014 ($P < 0.05$). Annual WUE was highest for SMSW, significantly exceeding both SMRF and WS, with SMSW and SMRF showing 24.8% and 0.3% higher WUE than WS, respectively. Single-season WUE ranked SMSW > SM (summer maize) > SMRF > WW (winter wheat). Summer maize WUE was lowest in 2012 due to excessive rainfall causing waterlogging and increased non-productive evaporation. From 2012-2014, SMSW, SM, and SMRF achieved 29.2%, 8.4%, and 3.9% higher single-season WUE than WW, respectively.

2.3.2 Economic Benefit Comparison Analysis

Economic benefits differed significantly among patterns from 2012-2014 ($P < 0.05$). WS benefits ranged 16,543.7-20,477.0 yuan · hm ^{2}, SMSW 13,170.1-21,046.0 yuan · hm ^{2}, and SMRF 10,244.4-13,427.7 yuan · hm ^{2} (). Average benefits for SMSW and SMRF were 5.2% and 36.8% lower than WS, respectively. Single-season benefits ranked SMSW > SMRF > SM (summer maize) > WW (winter wheat), with SMSW, SMRF, and SM achieving 153.6%, 68.9%, and 67.3% higher benefits than WW, respectively.

2.3.3 Economic Water Use Efficiency

Economic water use efficiency (EWUE) showed significant differences among patterns and crops from 2012-2014 ($P < 0.05$) ([Figure 4: see original paper]). SMSW EWUE was significantly higher than SMRF and WS, with SMSW and SMRF achieving 56.7% and 17.5% higher EWUE than WS, respectively. Winter wheat EWUE was significantly lower than other treatments, 51.9% and 35.9% lower than SMSW and SMRF, respectively. Within the WS system, WW EWUE was 39.1% and 24.7% lower than SM and the full WS rotation, respectively.

3.1 Water Consumption of Different Crops and Cropping Patterns

The WS system is the dominant cropping pattern in Hebei Lowland Plains, where extensive research has focused on water-saving and high-yield technologies for winter wheat, summer maize, and their rotation [20-22]. This study adopted the "Wuqiao Model" developed by Wang et al. [23-24], achieving WS annual ETa of 672.9-905.1 mm from 2012-2014. The 2012 wet year (with August rainfall far exceeding historical averages and causing localized waterlogging) recorded the highest ETa at 905.1 mm, while normal (2013) and dry (2014) years showed 780.9 mm and 672.9 mm, respectively—consistent with Liu et al. [25] who reported 800-900 mm for the North China Plain.

In WS, winter wheat consumed an average 384.2 mm, with irrigation (225 mm) accounting for 58.6% and rainfall (126.2 mm) only 32.9% of water use. Rainfall variability was low (coefficient of variation 6.1%), necessitating groundwater irrigation. Summer maize consumed 402.1 mm with 443.1 mm average rainfall, meeting water demand in wet and normal years, and providing 96.6% of needs even in the dry year.

SMSW and SMRF averaged 470.1 mm and 421.6 mm ETa, respectively, compared to 432.1 mm average rainfall. In the dry year 2014, soil water storage decreased by 35.9 mm (SMSW) and 88.1 mm (SMRF). SMRF experienced early-season drought stress (before mid-June), depleting soil water substantially. SMSW and summer maize showed minimal soil water change in wet and normal years, with moderate depletion in dry years. These results demonstrate that WS winter wheat depends heavily on irrigation and soil storage, while SMSW and SMRF rely primarily on rainfall, with fallow period precipitation effectively recharging soil moisture.

3.2 Yield of Different Cropping Patterns

Under current technology, WS maintains yield advantages over SMSW and SMRF. Liu et al. [26] reported spring maize mono-cropping yield losses exceeding 40% compared to WS, proposing a spring maize-winter wheat-summer maize 2-year, 3-crop system to reduce losses below 20%. This study found average annual yield reductions of 24.3% (SMSW) and 45.7% (SMRF) versus WS.

Spring maize traditionally shows higher yield potential than summer maize due to flexible sowing dates and access to longer-maturity varieties, whereas summer maize is constrained by winter wheat harvest timing, limiting variety selection. Dai et al. [15] reported spring maize yield potential of 13,000–16,000 kg · hm ^{2} in this region. Through continuous optimization of spring maize production technology, the yield gap narrowed during the experimental period, with SMSW reaching 12,072.8 kg · hm ^{2} in 2014—only 22.0% below WS. WS yields averaged 14,236.3 kg · hm ^{2} (coefficient of variation 9.3%), indicating relatively stable production. WS winter wheat yields (5,586.9–8,208.1 kg · hm ^{2}) and summer maize yields (6,956.4–8,001.7 kg · hm ^{2}) were consistent with Wang et al. [23]. Across all systems, single-season yields ranked spring maize highest, followed by summer maize, with winter wheat lowest.

3.3 Water Use Efficiency, Economic Benefits, and Economic Water Use Efficiency of Different Cropping Patterns

Water use efficiency is central to sustainable agricultural development in water-limited regions [27]. SMSW achieved significantly higher WUE than WS and SMRF. WUE was higher in dry years than wet years because concentrated summer rainfall (July–August) coincided with peak temperatures, increasing non-productive evaporation—exemplified by waterlogging in August 2012. SMRF was limited by low early-season rainfall (May–June), reducing emergence rate and uniformity; supplemental irrigation during this period would substantially improve yields. In WS, winter wheat' s low single-season yield and C3 physiology (versus C4 maize) resulted in significantly lower WUE, consistent with Yang [28].

Economic analysis revealed that as spring maize technology improved, the net benefit gap between SMSW and WS narrowed. Single-season net benefits ranked

SMSW > SMRF > SM > WW, with WW disadvantaged in both yield and price. Notably, spring maize’ s earlier market arrival coincided with supply shortages, commanding price premiums over summer maize. Additionally, current irrigation cost calculations excluded water pricing, which scholars propose implementing [29]. Under such a policy, the SMSW-WS benefit gap would further narrow. From 2012-2014, WW showed the lowest EWUE, while SMSW achieved the highest. Spring maize’ s high yield potential and superior rainfall coupling enabled substantial economic returns from minimal irrigation, indicating tremendous potential for systematic water saving through cropping system adjustment.

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